

NON-FIRED LATERITE SOIL BRICKS WITH NA-BASED STABILIZER ADDITION FOR SUSTAINABLE DEVELOPMENT

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Abstract

Fired bricks are widely used, but they are energy-intensive and non-eco-friendly. Non-fired bricks with chemical stabilisers can be the alternative solution, which is a low-energy-intensive and environmentally friendly manufacturing product. Laterite soil can be the raw material for the synthesis of non-fired clay brick in sodium hydroxide solution and sodium silicate solution. However, it may have been mixed with other laterite soils with different optimum moisture contents and grain sizes during extraction. Thus, the mixing ratio of laterite soil, Na-based stabilisers, and water for non-fired brick production is determined. Besides, two types of laterite soil, LAT 1 and LAT 2, from different locations were prepared, and another type of laterite soil, LAT 3, was prepared by mixing LAT 1 and LAT 2. Both three are compared primarily in terms of compressive strength and water absorption, which are mixed with the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio. As a result, the new mixing ratio with increased water content was determined based on the optimum moisture content of the soil. Besides, the optimum mixing ratio of each type of brick was determined. Overall, based on the Malaysian standard, all types of brick samples from each ratio could be used as load-bearing class 1 and internal wall bricks. Additionally, LAT 2 and LAT 3-based bricks with a ratio of 1.5 $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio can be used as load-bearing brick class 2.

Keywords: Compressive Strength; Laterite Soil; Mixing Ratio; Na-Based Stabilisers; Non-Fired Bricks; Water Absorption

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Introduction

Clay brick is the most common, universal, and oldest building material used by mankind for thousands of years. It is made from clayey soil and water with the required technical knowledge, forms, and dimensions that can be used as one of the accessible building materials to build shelters in ancient times such as the Mesopotamian, Egyptian, and Roman periods (Dalkılıç and Nabikoğlu, 2017). The first brick was a small, sun-dried lump of mud or clay by 3000 BC, which evolved into moulded units of sun-dried mud made from cattle dung or straw. High-quality bricks in terms of strength and durability were invented by firing bricks in clamps, as shown in Figure 1, and were further improved after constructing a kiln. The first patent for a brick manufacturing machine was issued in 1619, and the introduction of the Hoffman kiln allowed for continuous production of bricks, which increased the rate of mechanical brick production in 1985 (Robert *et al.*, 1994). Manufacturing methods combined with technology result in a different variety of fire bricks being used today and available worldwide. They are considered one of the most widely used building materials for a variety of civil engineering construction structures (Stacy, 2007).



Figure 1. A typical clamp-form brick kiln in Karad, India (Kulkarni and Rao, 2016)

Nowadays, the world is facing global warming that causes climate change due to the greenhouse effect. It is due to rising levels of greenhouse gases such as carbon dioxide. The brickmaking industry is known to contribute one of the most significant amounts of greenhouse gases in the world (Akinshipe and Kornelius, 2017). There are about 70-282 g of carbon dioxide, 0.001-0.29 g of black carbon, 0.29-5.78 g of carbon monoxide, and 0.15-1.56 g of particulate matter per kg of brick fired that are emitted (Murmu and Patel, 2018). Moreover, the fired brick needs an extremely high temperature of about 1000-1500 °C for processing the raw materials, which is not friendly to the environment with an estimation of 2500 MJ of average energy consumption, which is approximately twice that of

one tonne of concrete, which is about 1200 MJ (Bastianoni *et al.*, 2006). Thus, this makes it energy-intensive, non-eco-friendly, and costly.

As the world population increases, the demands for shelter are getting higher, but the supply of affordable shelter is getting lower due to the higher price of construction materials. In terms of green sustainable construction materials, non-fired brick with sodium stabiliser or geopolymers brick, as shown in Figure 2, is being developed. It is a low-energy-intensive manufacturing product that cures at around 100°C and emits a low amount of carbon dioxide (Iftikhar *et al.*, 2020). About 80 percent less carbon dioxide is released from manufacturing geopolymers brick as compared to conventional brick (Muheise-Araalia and Pavia, 2021). Hence, it is an alternative solution by producing low-embodied brick, which can be manufactured at a lower temperature level.



Figure 2. Fly ash based geopolymers bricks (Subramani *et al.*, 2016)

Geopolymer is synthesised in the reaction of an aluminosilicate precursor (raw aluminosilicate) with a highly concentrated alkali activator solution (Reeb *et al.*, 2021). Clay is widely available and can be used as an aluminosilicate precursor in alkaline solutions for the synthesis of geopolymers (Ababneh *et al.*, 2020). Normally, clays such as kaolinite, halloysite, and illite are activated to improve the mechanical properties of the geopolymer through calcination. The calcination of the kaolin is typically done at a temperature of 700-850 °C with a consumption of 600-700 kcal/kg and a total of 200-300 kg of CO₂ emitted per tonne of calcined kaolin to form amorphous metakaolin (Ghani *et al.*, 2021). As a result, the high temperature needed and the high carbon emissions in the calcination make it an unsustainable manufacturing process.

Laterites, which are common in tropical areas and generally exist at the surface, are an alternative material to clays, which can harm the environment through exploitation. It is sourced locally, which

means it has a low transportation cost. As a result, it contributes to high energy efficiency and profitability. Originally, the laterite soil contained fewer nutrients and organic matter (Dwevedi *et al.*, 2017) but partly contained kaolinite, which is rich in alumina and silica. The higher the degree of laterization, the more corroded the laterite is and the more amorphous its properties are, requiring no calcination prior to geopolymerisation. Hence, it can be referred to as “clean and sustainable production” as it is energy efficient, which can save energy from the thermal calcination.

Calcined soil has risen in popularity in geopolymer research, such as research by Parthiban *et al.* (2022), Zhang *et al.* (2022), Yuan *et al.* (2021), and Mohseni (2018). However, the calcination process is energy-intensive and makes it costly, which goes against the sustainability benefits of using alkali-activated clay brick, which has a high embodied energy and has the potential to cause global warming. Therefore, the laterite soil without calcination is considered, which may contribute to drawbacks in the properties of geopolymer formation in terms of compressive strength and water absorption. Based on the studies, there are numerous types of non-fired bricks with different raw materials and stabilisers (Iftikhar *et al.*, 2020; Ghani *et al.*, 2021; Morsy *et al.*, 2022). As a summary of the findings, the compressive strength and water absorption characteristics of the bricks are dependent on the raw materials, especially for low-quality bricks produced from clay without calcination as a raw material due to the low reactivity of clay with alkali medium. Others with thermal treatment and high compacting pressure, on the other hand, will have high compressive strength and low water absorption.

The purpose of this research was to determine the mix ratio of laterite soil, sodium silicate solution, sodium hydroxide solution, and water for non-fired brick production via compressive strength and water absorption tests and to determine the optimum compressive strength and water absorption characteristics of the non-fired brick with field

application considerations according to the Malaysia Standard, British Standard, Singapore Standard, American Standard, and Australia Standard.

Material and Methods

Brick samples were prepared with three types of laterite soil samples: laterite soil 1 (LAT 1), laterite soil 2 (LAT 2), and mixed laterite soil (LAT 3) with sodium-based stabilisers. In addition, three types of control samples without sodium-based stabilisers were prepared according to each type of laterite soil. Two types of brick samples were made from two kinds of laterite soil (LAT 1 and LAT 2), which were acquired from different locations, while the third type of brick sample was made from a mixture of the two kinds of laterite soil (80% LAT 2 and 20% LAT 1). The compaction test, dry sieve analysis, and pH value determination were based on Technical Committee RDB/38, (1990).

The materials used to manufacture brick include laterite soil, sodium silicate, sodium hydroxide solution, and water. A total of six mix designs have been prepared, and one mix design acts as a control sample without sodium silicate and sodium hydroxide solution. As the sodium-based stabilisers were prepared, different mass ratios of sodium hydroxide and sodium silicate.

The solution were prepared, while the mass ratio of laterite soil remained constant. Due to the higher optimum moisture content (OMC) of the soil sample than the industry's soil samples, the water was increased from 10 to 15 in terms of ratio based on the result of the compaction test. Two of the mass ratios for the preparation of alkali activator were provided by the industry, and the remaining is customised as shown in Tables 1 and 2. Furthermore, because the provided mix design is based on dried clay, the soil sample was prepared by drying for 24 hours.

Due to the limitations of the equipment, half-size bricks were manufactured instead of full-size bricks. There are four stages in the brick

Table 1. Mixing the proportion of the bricks in terms of the ratio

No.	Laterite soil	Na ₂ SiO ₃	NaOH	Water	Na ₂ SiO ₃ / NaOH ratio
1	100	6.5	7	15	0.9
2	100	7	6.5	15	1.1

Table 2. Mixing the proportion of the bricks in terms of the mass

No.	Laterite soil (g)	Na ₂ SiO ₃ (g)	NaOH (g)	Water (g)	Na ₂ SiO ₃ / NaOH ratio
1	1500	97.5	105	225	0.9
2	1500	105	97.5	225	1.1
3	1500	112.5	90	225	1.3
4	1500	127.5	82.5	225	1.5
5	1500	135	75	225	1.8
6	1500	-	-	345	-

manufacturing process: mixing, shaping, curing, and cooling. At first, laterite soil was weighed according to the mix proportion and placed into the bowl of the mixture. 12.3 M concentrations of NaOH solution (48.5-50% sodium hydroxide and 50-51.5% water) and Na_2SiO_3 solution (37.3-40% Na_2SiO_3 and 60-62.70% water) were used for this research and the water added will be compensated based on the percentage of water in each solution. They are weighted according to the mix design and mixed for a maximum of 3 to 4 minutes. The mixed solution was poured into the laterite soil in the mixer's bowl and mixed until the colour was uniform, no more than 4-5 minutes. Next, 1.70 kg of the fresh mixture was weighted and filled in the steel mould. Then, the wood topping was placed on top of the mould filled with the mixture and was pressed at a pressure of 3 MPa using a cold-press machine. The whole mould was moved away from the cold press machine, and the sample with the desired height was demolded. The width and length of the compacted mixture were marked and trimmed with a putty knife. A total of four samples can be manufactured from one compacted mixture. It was followed by the recording of the dimension and mass of the samples. All the bricks were placed in a 50°C binder oven for 48 hours after shaping immediately. After the 50°C curing, all the bricks were placed in a 200°C aggregate oven for another 24 hours. All the bricks were cooled at room temperature for 12 hours. According to the findings by Kamseu *et al.* (2020), curing conditions should be specified for an effective geopolymerisation process. Curing temperature in the range of 50 to 100 can enhance the transformation and rate of reaction which results in optimum formation of ferrosilicates and ferrisilicates. Once enough polynuclear ferrosilicates and ferrisilicates have formed, the alkalinity of the medium is increased to a level that is suitable for the formation of the geopolymer without forming the iron hydroxide complexes that precipitate, which can inhibit the process of geopolymerisation. Furthermore, a temperature of between 50 and 200 °C, a crystalline structure is formed from the amorphous gel. main characteristic tests conducted, which are compressive strength and water absorption tests, and this study was mainly There is a relevance to the manufacturing process given by the industry whereby the curing temperature at 50°C for 48 hours and heating temperature at 200°C for 24 hours. Lastly, the dimensions and mass of the samples were recorded again. There are two based on MS 76: Part 2: 1974 and BS 3921: 1985. The method of compressive strength and water absorption tests on brick samples are based on MS 76: Part 2: 1974, while the range of tolerance for the dimensions of

the bricks was according to Technical Committee CLB/7, (1985).

Literature Review

Geopolymer

Geopolymer can be known as an inorganic polymer with atoms of silicon, phosphorus, oxygen, or nitrogen in its backbone rather than the backbones that essentially contain carbon atoms in organic polymers (James *et al.*, 1963). Mineral polymers and inorganic polymer glasses are other names for them (Hos and Byrne, 2002). According to Khale and Chaudhary (2007), the inorganic polymer is called geopolymer because it is defined as an amorphous equivalent of geological feldspars with a production process similar to that of organic polymers. French materials scientist and archaeologist Joseph Davidovits, known as the "Father of Geopolymers," invented geopolymer, which is the product of binder, and the chemical process of geopolymerisation in 1979 (Davidovits, 2020). The reactions occur simultaneously and can be summarised as dissolution, condensation, settling, and hardening. Geopolymer is similar to zeolite, but its microstructure is amorphous and semi-crystalline with a three-dimensional alumina-silicate (Karslio and Onur, 2021) in four-fold coordination. Aluminosilicate sources are defined as source materials that are abundant in silica with moderate alumina content (Tennakoon *et al.*, 2014). The chemical composition of the precursor, which is the alumino-silicate material as the main raw material, and the activator, which is the alkaline solution as the second raw material, determines how geopolymer is used in a variety of applications, including fire-resistant fibre composites, coatings, mortar, concrete, and ceramics (Hanafi *et al.*, 1980). Moreover, its cementitious properties as a binder would be beneficial for its application in the construction industry. Besides, the degree of reactivity of the raw material is one of the priority factors that contribute to the strength of geopolymer, so the raw material should contain significant amounts of both active alumina and silica (Zhang *et al.*, 2022).

Precursor

Geopolymer precursor materials must be high in alumina (Al_2O_3) and silica (SiO_2) content, with a preference for the reactive amorphous form, which is responsible for the cement's strength and setting properties (Farhan *et al.*, 2020). Generally, laterite soils are made up of a $\text{Fe}_2\text{O}_3(\text{FeO})\text{-SiO}_2$ - matrix that results from kaolinite mineral alteration, which has a high proportion of Al^{3+} occupying the octahedral

Table 3. Chemical composition for laterite soil

References	Chemical Properties			
	SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	Others (%)
Abdullah <i>et al.</i> , 2017	42.00	35.00	19.00	4.00
Latifi <i>et al.</i> , 2016	25.46	31.10	35.53	7.91
Zolfeghari Far <i>et al.</i> , 2013	33.55	22.31	19.40	24.74

sites comprising iron Fe²⁺ or Fe³⁺. There are a few studies of the chemical properties of natural laterite soil in Malaysia, as shown in Table 3.

Alkali activator

Alkali reactant is a soluble alkali metal based on sodium or potassium. The type and concentration of the alkali reactant can affect the rate of dissolution of alumina-silicates. Moreover, high pH values of an alkali reactant, such as at pH 14, induced higher dissolutions of Al and Si from the raw materials than at pH values of 12, especially the Al. It produced more oligomers and resulted in an insoluble and strong polymeric matrix (Phair and Van Deventer, 2002). Generally, the mixture of hydroxide and silicate solution is used as an alkali reactant solution, such as sodium hydroxide and sodium silicate solution. However, geopolymers made from a mixture of potassium hydroxide and potassium silicate have better mechanical characteristics than those made from sodium hydroxide and sodium silicate (Gharzouni *et al.*, 2015). Last but not least, high alkali concentrations can cause serious efflorescence, which affects the appearance. It occurs in systems that are abundant in silicon, but the degree of efflorescence decreased with the alkali amount as the alumina concentration increased (Xiao *et al.*, 2020). However, according to Wang *et al.* (2018), the frequency of the efflorescence of geopolymers reduces with increasing silica concentration and smaller silica particle size.

According to Abdullah *et al.* (2011), as there is an excess hydroxide ion concentration in the mixture, the excess sodium ions from sodium hydroxide and sodium silicate that are not reacted can be converted to sodium carbonate, which will interfere with the polymerization process and affect the geopolymer properties.

Factors of affecting characteristics of the geopolymer

Different conditions indicate the growth of the microstructure of the geopolymer. There are some factors that will affect the characteristics of the geopolymer, such as the ratio of Na₂SiO₃/NaOH, and water.

Ratio of Na₂SiO₃/NaOH

Na₂SiO₃ has the ability to increase the condensation rate by providing more sodium ions

and silicates. However, the high content of sodium silicates, which contain a high amount of sodium ions, results in their self-condensing at a fast rate from solution into gel. This contributes to a less compact structure and results in a loss of strength. Moreover, based on Tome *et al.* (2020) sodium silicate can initiate different kinds of oligomers and the subsequent polycondensation process, but the mechanical properties will be affected if it is present in excess. It can be explained by the pH value of the sodium silicate being about 11, which makes the environmental conditions less alkaline for the Al and Si dissolutions from raw materials and the geopolymerisation process. While NaOH solution has a pH value of about 14, that can provide strong alkaline environmental conditions. Therefore, based on Jin *et al.*, and Poloju and Srinivasu, there is the idea that both sodium hydroxide and sodium silicate as the alkali activator can enhance the whole geopolymerisation process by fastening the geopolymerisation process, densifying the microstructure of the product, and resulting in high compressive strength. In addition, the compressive strength is further increased as the sodium silicate is increased. It is possible to conclude that a mixture has no effect on itself but has a positive effect on others.

Different Na₂SiO₃/NaOH ratios would result in different compressive strengths. The compressive strength increases as the Na₂SiO₃/NaOH ratio increases until it reaches an optimum. Beyond this point, the compressive strength was found to decrease. According to Lee and Deventer (2004) and Villa *et al.* (2010), a high Na₂SiO₃/NaOH ratio will contribute to a decline in compressive strength with a rise in sodium silicate due to a high polymerization reaction that contributes to aluminosilicate gel precipitation in very early stage that restricts contact between the reacting material and the activating solution and lowers activator concentration. In addition, it is also caused by the defective structure that was mentioned previously.

In terms of workability, as the Na₂SiO₃/NaOH ratio increased, the workability of the mixes decreased due to the high content of viscous sodium silicate solution (Malkawi *et al.*, 2016). In respect to the economic factor, the ratio should be low while still meeting the requirements of compressive strength and workability due to the fact that sodium hydroxide costs less than sodium silicate. Therefore,

the geopolymer materials required to be strengthened must be strengthened using a highly alkaline solution with the right amount of silica.

In short, a high $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio can enhance mechanical characteristics and microstructure and speed up the polymerization process, while high sodium silicate contributes to a high polymerization reaction resulting in aluminosilicate gel precipitation in a very early stage and a decline in compressive strength.

Water

The total amount of water in the mixture is equal to the sum of the water in the sodium silicate solution, the sodium hydroxide solution, and the added water. According to Bakri *et al.* (2011), water is required to act as a reactant for the dissolution of aluminosilicate materials and the hydrolysis of dissolved aluminium and silicon ions to produce monomers. Figure 3 depicts the stages of geopolymerisation with water as a catalyst. More water can accelerate the dissolution and hydrolysis, as there is a high hydroxide concentration. At the same time, water is the product of the polymerization and polycondensation processes that produce oligomers and semi-crystallized polymers. The reorientation process begins once a small amount of water is removed, and the water is almost completely removed during hardening at 20°C or higher. However, if the water content is higher than the optimum limit, the polymerization processes will be affected. According to Zuhua *et al.* (2009), too much water will impede the rate of polycondensation resulting in low compressive strength and good water absorption of the geopolymer due to its increased porosity with an increase in pore volume and size. In addition, the excess water does not contribute to the formation of

the framework structure of the geopolymers and leads to low bulk density. By contrast, the low water content results in high bulk density and mechanical strength (Okada *et al.*, 2009). Hence, water molecules have a significant impact on the formation of geopolymers in terms of structure and characteristics.

According to Barbosa *et al.* (2000) a sufficient amount of water can aid mixing and provide an ionic transport mechanism. As there is excess water, the concentration of the alkali solution will be diluted, or the more soluble components will be leached and transported away from the reaction zone. As a result, the rate of dissolution and reaction of the geopolymer decreased. Furthermore, water dilutes the alkaline solution. Thus, the less water used, the less alkaline solution should be added to achieve the desired concentration so that the dissolution process can take place and result in economic benefit.

Fresh geopolymer is easily workable at low water content. High water content makes the preparation stage easier, such as mixing, due to its high workability and low viscosity, but the compressive strength of the geopolymer will be reduced once it is hardened. In contrast, the lower water content makes for a more compact structure with increased strength development (Xie and Kayali, 2014). It is supported by the study of Khale and Chaudhary (2007), compressive strength decreases when the water-to-solid by-mass ratio increases. According to Manjarrez *et al.* (2019) in low amounts of water below the optimum value in the mixture, lumps form and big voids develop in the specimens, resulting in low compressive strength, while in high amounts of water beyond the optimum value, more water is available in the mixture, which will decrease the particle interference due to the increased interparticle distance and result in low compressive strength.

In summary, compressive strength increases when the water-to-solid ratio is lower and vice versa. Excess water results in a more porous structure and leads to a low bulk density. Moreover, the concentration of the alkali solution will be diluted, and more soluble components will be leached away from the reaction zone, which will contribute to low compressive strength.

Geopolymer brick

There are two main characteristics of geopolymer bricks that were studied: compressive strength and water absorption. In addition, the density is determined due to the formation of microstructure related to the compressive strength and water absorption.

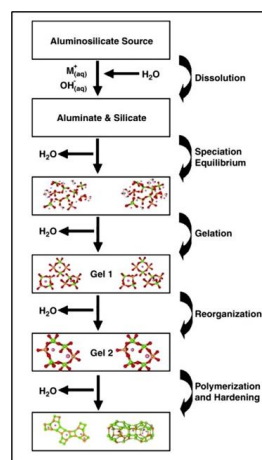


Figure 3. Schematic diagram of geopolymerisation (Li *et al.*, 2010)

Compressive strength

Compressive strength is the defining characteristic of all structural materials. It is the most important parameter in a construction material to evaluate its engineering quality, measure its ability to sustain the load, and determine its suitability for the architectural choice (Ukwatta and Mohajerani, 2017). For geopolymer brick, its compressive strength is a crucial characteristic since it shows how well the solid aluminosilicates and alkali sources react with one another. A greater ability to resist compression shows that the bricks have a much superior microstructure and better durability. (Thejas and Hossiney, 2022). In addition, the indicators of denser microstructures are higher bulk density, decreased porosity, and low water absorption (Ranjbar *et al.*, 2017). According to Singh *et al.* (2015), the compressive strength exhibits significant differences even when utilising the same materials. It is definitely based on its reactivity according to the chemical composition, mineralogical composition, morphology, fineness, and glass phase content.

The optimal alkali activator concentration can enhance the geopolymer's strength. As the concentration of the alkaline activator increases, the pH of the activating solution increases as well. According to Oyebisi *et al.* (2018), pH values in the 13-14 range are appropriate for polymer development with higher mechanical strengths. The geopolymer with a high Si/Al ratio has a higher proportion of Si-O-Si bonds, which are stronger than Si-O-Al bonds and contribute to higher strength (De Jong and Brown, 1980).

In short, the compressive strength of a geopolymer is affected by the NaOH molarity, the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio, the pH value of the alkali activator, the microstructure, and the glass phase of the raw materials. They can affect the geopolymerisation reaction, such as the rate of dissolution of the aluminosilicate materials and the formation of cross-linking in the aluminosilicate gel that contributes to the microstructure that played a role in the development of compressive strength. Compressive strength can be enhanced by the denser structure due to the gaps and pores being filled during geopolymerisation and the high dissolution of the solid precursor that results in high geopolymer matrix extension.

Water absorption

Good durability is the main feature of the construction structure in terms of sustainable development to prolong the service life of the structure, which can reduce carbon dioxide emissions and waste produced in future redevelopment (Li *et al.*, 2020). It is the ability of a structure to resist

severe environmental and weather conditions, such as water attacks (Babé *et al.*, 2021). This is a significant consideration with building materials, particularly in tropical areas where rain is frequent.

Brick is a porous substance, and water absorption from the outside is controlled by capillary action (Groot and Gunneweg, 2010). This is due to surface tension forces that cause water absorption through small openings and the diameter of the capillary tubes. In addition, the temperature will affect the distance water transfers (David, 1997). The ability of a brick to absorb water is a crucial characteristic that will affect the porosity and durability of the brick (Kuranchie *et al.*, 2016). For geopolymer brick, the geopolymer's structural formation determines how much water the bricks absorb.

Moreover, water absorption is based on the number and size of pores in bricks. The greater the number of pores and the larger the size of the pores, the more water absorption the bricks may achieve (Phonphuak, 2013). Porosity and water absorption are inversely proportional to compressive strength. Cementitious materials with a large porosity will absorb more water and contribute to low strength gains. The water absorption capability can be further decreased with hot curing, eventually resulting in a compact and dense microstructure that prevents water and other ions from entering the system. The rate of absorption decreases with time as the reaction is completed. However, according to Ahmari and Zhang (2012), water absorption increases from 2 to 5 percent when the forming pressures increase from 0.5 to 15 N/mm². This is due to the fact that the leaching of liquid from the plastic mixture tends to cause a reduction in the geopolymeric gel, which affects the brick's properties and makes it porous and permeable at higher compaction conditions. Hence, the water absorption of the samples should be carried out in a standard water absorption test to further verify the performance and durability of the sample.

In short, water absorption is affected by the porous structure of the geopolymer formation. Under curing conditions of elevated temperatures and adequate compaction pressure, an effective geopolymerisation process and compacted structure with fewer accessible voids and less capability of retaining water can be achieved.

Fired brick

Brick is produced using clay or shale that has been formed, dried, and fired (Brick Industry Association, 2006). There are different classifications of fired clay brick according to the following standard for identification for the manufacturer and buyer based on the application.

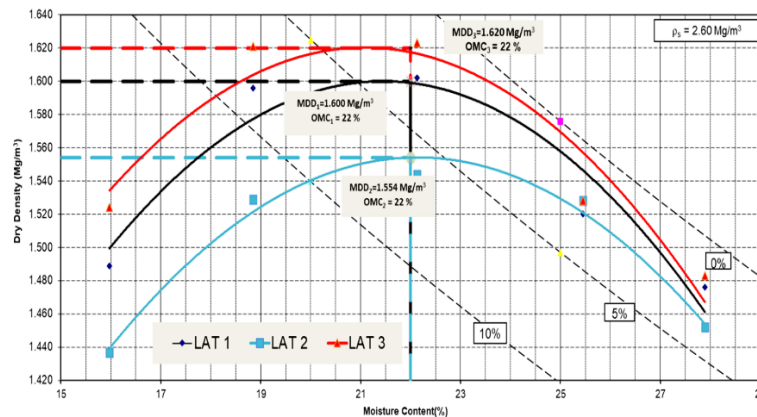


Figure 4. Graph of dry density of laterite soils against moisture content

Table 4. Summary of specification and classification according to five countries of standards

Country (Standard/ References)	Type of brick	Minimum compressive strength (MPa)	Maximum water absorption (%)
Malaysia (Civil Engineering and Building Construction Industry Standards Committee, 1972)	Engineering brick	48.5-69.0	4.5-7.0
	Loadbearing brick	7-103	-
	Damp proof courses	As per required	4.5
	Facing and common bricks of ordinary and unique quality	5.2	-
British (Technical Committee B/526, Geotechnics, 1999)	Engineering brick	50-70	4.5-7.0
	Damp-proof course	5	5-7
	Others	5	-
Singapore (SPRING Singapore, 1974 and Brick Industry Association, 2006)	First-grade brick	35	25
	Second-grade brick	20	
	Third-grade brick	5.2	
America (Mawlood and Amen, 2009 and Kuranchie <i>et al.</i> , 2016)	Building brick	8.6-17.2	20-25
	Facing brick	15.2-17.2	17
Australia (SPRING Singapore, 1974 and Brick Industry Association, 2006)	No specific	5-7	-

For comparison, in terms of the water absorption of high-quality brick, Malaysian and British standards have strict requirements for engineering brick, in which the maximum water absorption is in the range of 4.7-7.0%. While the others are not as strict as the Malaysian and British standards, the maximum water absorption of building and facing brick in American standards is in the range of 20-25 percent and 17 percent, respectively; brick in Singapore standards is 25 percent; and there is no requirement for maximum water absorption of brick in Australian standards. The overall requirement in terms of compressive strength and water absorption according to each country's standard is summarised in Table 4. The total amount of water in the mixture is equal to the sum of the water in the sodium silicate solution, the sodium hydroxide solution, and the added water.

Results and Discussions

Compaction test

As a result, the OMC of LAT 1, LAT 2, and LAT 3 was 22 %, as shown in Figure 4. The result is critical for optimum mixing in the trial-and-error phase, as there was the issue of inconsistent mixing, and many lumps were formed using the industry's given mixing ratio. Hence, based on the OMC of LAT 1, the water was increased from 10 to 15 in terms of ratio in order to achieve a total of 22 % moisture content. However, the concentration of the alkali solution will be diluted as more water is added. It decreases the particle interference and affects the polymerization processes (Manjarrez *et al.*, 2019), which decrease the rate of dissolution and polycondensation and result in a less compacted and porous structure, which contributes negatively

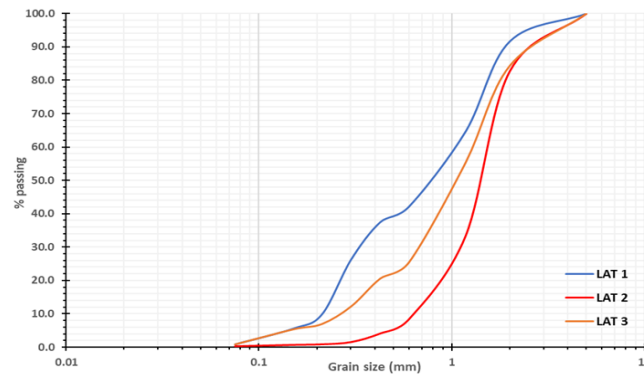


Figure 5. Plot of % passing vs. grain size distribution of all types of soil sample

Table 5. Summary of specification and classification according to five countries of standards

Type of laterite soil	Uniformity coefficient, C_u	Curvature coefficient, C_c	Percentage of coarse-grained sand (%)	Percentage of medium-grained sand (%)	Percentage of fine-grained sand (%)	Percentage of the soil finer than 0.06 mm (%)
LAT 1	4.95	0.52	57.90	32.32	9.4	0.38
LAT 2	2.74	1.09	91.66	7.54	0.69	0.11
LAT 3	4.83	1.42	74.51	18.51	6.59	0.39

to the compressive strength and water absorption characteristics unless the alkali solution is also added according to the previous ratio of water to alkali solution. Therefore, the specific characteristics of brick cannot be achieved according to the mixed design of the industry in this study.

Dry sieve analysis of laterite soil

As a result, based on Figure 5 and Table 5, both were slightly silty sands. As a comparison in terms of grade, LAT 1 was gap-graded, slightly silty sand with two gaps within the size range of 0.6 mm to 0.425 mm and 0.075 mm to 0.063 mm, whereas LAT 2 was well-graded, slightly clayey sand with uniform particle sizes ranging from 1.6 mm to 0.64 mm. Therefore, LAT 2 could be compacted more easily than LAT 1, eliminating voids by interlocking the particles and resulting in a dense structure. Furthermore, LAT 3 was well-graded within a large variety of particle sizes but gap-graded within the size range of 0.6 mm to 0.425 mm, which can contribute to high maximum dry density with less air void that occupies the void space between the soil grains if compared to other grades of soil, as shown in Figure 4. As a result, the OMC of LAT 1, LAT 2 and LAT 3 was 22 % as shown in Figure 4.

Water absorption and compressive strength test

Based on the results in Figures 6 and 7, the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio is inversely linear proportional to the water absorption but is directly linear

proportional to the compressive strength for all three types of samples. This is due to the increased concentration of soluble silicate ions from Na_2SiO_3 . The compressive strength and water absorption of the geopolymer brick are related to the cross-linking aluminosilicate gel, which builds up the microstructure that determines the overall compactness of the structure. As the silicate is present in large quantities, geopolymerization produces stronger long-chain silicate oligomers. Besides, bricks absorb water more readily when there are more and larger pores than when there are fewer and smaller pores. In addition, compressive strength is inversely correlated with porosity and water absorption as shown in Figure 8 due to the dense structure with less porosity contributes to high strength gains and low absorption capability (Kuranchie *et al.*, 2016 and Mawlood and Amen, 2009). Therefore, the high $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio results in a product that is less porous, and has a high compressive strength (Jin *et al.*, 2021, Poloju and Srinivasu, (2022), and De Jong and Brown, 1980). Additionally, the optimum $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio is suggested to be determined in further research since both $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratios do not have a negative contribution to both compressive strength and water absorption. Hence, another $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio that is higher than 1.8 is suggested to be prepared. Moreover, after 24 hours of water absorption testing, the pH value of the water in the storage box was determined to be 11.4. It was shown that the water was alkaline, which indicates that there was a

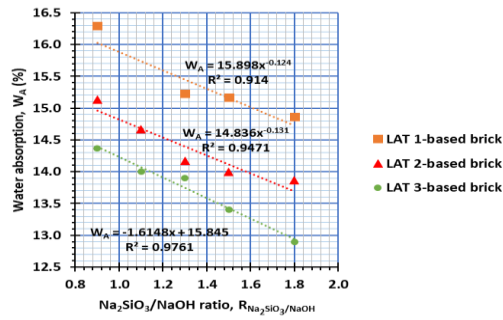


Figure 6. Water absorption of each type of brick samples according to each $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio

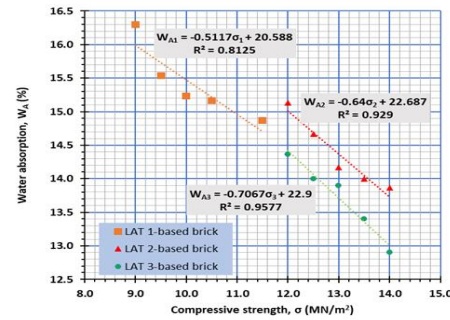


Figure 8. Relationship of water absorption and compressive strength of each type of brick sample according to each $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio

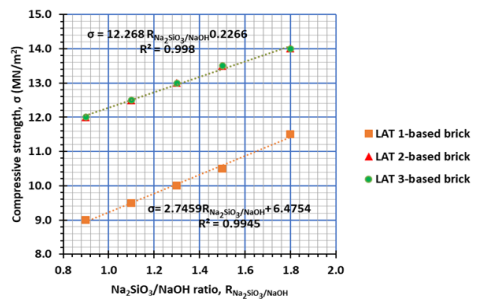


Figure 7. Compressive strength of each type of brick samples according to each $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio



Figure 9. LAT 1-based controlled brick sample after 24-hour water absorption test

high leaching of Na-stabilisers by the water from the brick. Therefore, the external wall is not permitted as an application.

Furthermore, each of the samples is parallel to each other's. Referring to the Figure 8, the compressive strengths of LAT 2 and LAT 3-based brick samples were the same for each $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio, though greater than those of LAT 1-based brick. Besides, the lowest water absorption is in the LAT 3-based brick samples for each $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio. It is followed by the LAT 2-based brick samples, and the highest water absorption is in LAT 1-based brick samples. It is due to the different particle size distribution of soil, which results in different interlocking of the soil particles after compacting. In short, the grain size distribution is critical whereby well-graded soil results in high compactness of the soil structure with less porosity, contributing to the high performance of geopolymer brick in terms of compressive strength and water absorption characteristics, with an improvement of 3 MPa of compressive strength and a decrease of 1.3-2.0% water absorption as compared to gap-graded soil.

Water absorption and compressive strength test

Overall, water absorption is inversely proportional to compressive strength, whereby geopolymerization generates dense and stronger long-chain silicate oligomers as there is a high concentration of silicate ions in the Na_2SiO_3 solution. However, a high $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio will contribute to a decline in compressive strength with a rise in sodium silicate due to a high polymerization reaction that contributes to aluminosilicate gel precipitation in very early stage that restricts contact between the reacting material and the activating solution and lowers activator concentration. Since neither the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio contributes negatively to compressive strength and water absorption, additional study is recommended to identify the optimum $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio, as stated in the previous section, that is greater than 1.8.

Based on the control brick samples shown in Figure 9, there were many cracks that formed on the control samples and disintegrated when taken out of the water after a 24-hour water absorption test. Hence, it indicated that the control samples do not have resistivity to water attack. While the result of

the compressive strength was shown in Table 6, overall, the control brick samples were on average between 3.8 and 3.9 MPa, which fails to meet the minimum compressive strength of 5 MPa. Hence, it can be deduced that the sodium stabilisers have effectively increased the engineering and durability properties of the laterite soil-based brick. According to the past reports by Abdullah *et al.*, 2017, Latifi *et al.*, 2016, and Zolfeghari Far *et al.*, 2013, laterite soil meets the requirement of forming the geopolymer matrix by Na-based stabilisers due to high levels of aluminosilicates and iron. As a result, sodium stabilisers play an important role in reacting with laterite soil to form the geopolymer matrix, which acts as a binder. In conclusion, all brick samples of each ratio could be applied based on different standards, as shown in Table 7, while LAT 2 and LAT 3-based bricks at a ratio of 1.5 of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ can also be applied as load-bearing brick class 2 based on the Malaysian Standard.

Comparison of fired and non-fired bricks

The fired and non-fired bricks are compared with respect to the manufacturing phase in terms of electric consumption, cost, and carbon footprint. The electric consumption is based on the power consumed by the equipment. Non-fired brick is cured at 50°C for 48 hours and dried at 200°C for 48 hours in the oven. While the fired brick is fired in the furnace for 30 hours at 1000°C. The cost is computed by referring to the tariff rates of Tenaga Nasional Berhad (TNB). According to the UK Government GHG Conversion Factors for Company Reporting, the carbon footprint, CO_2e , is computed based on electric consumption, as shown in Table 8. As a result, there are three times fewer carbon emissions from non-fired bricks if compared to fired bricks.

Table 6. Compressive strength of controlled-based brick

Type of soil	Sample no.	Length (mm)	Width (mm)	Area (mm)	Force (kN)	Compressive strength (MN/m ²)	Average compressive strength (MN/m ²)
LAT 1	1	105.1	51.1	5370.61	20.431	3.8	3.8
	2	105.2	52.1	5480.92	21.494	3.9	
	3	106.2	51.5	5469.30	20.627	3.8	
LAT 2	1	107.1	51.8	5547.78	22.41	4.0	3.9
	2	106.3	50.5	5368.15	21.987	4.1	
	3	107.0	51.9	5553.30	20.112	3.6	
LAT 3	1	106.9	49.3	5270.17	22.367	4.2	3.8
	2	106.4	50.1	5330.64	17.726	3.3	
	3	106.2	51.5	5469.30	20.916	3.8	

Table 7. Compressive strength of controlled-based brick

Standard	Min. σ (MN/m ²)	Max. W_A (%)	Application	Remarks
Malaysian	14.0	-	Load bearing brick class 2	LAT 2 and LAT 3-based brick samples for a $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio of 1.5
British	7.0	-	Load bearing brick class 1	All types of brick for each ratio
	5.2	-	Internal wall brick	
	5.0	-	All excluded engineering and damp-proof course brick	
Singapore	5.2	25	Third grade brick	
America	8.6	-	Non-weathering building brick	
Australia	5 and 7, respectively	-	≤ 0.7 and 2 of ratio height to width	

Table 8. Field application of geopolymer brick according to each standard

Non-fired brick	Type of brick	Fired brick
$0.3\text{kW} \times 48\text{h} + 0.7\text{kW} \times 24\text{h} = 26.4\text{ kWh}$	Electric consumption (1 pcs)	$2.0\text{kW} \times 30\text{h} = 60\text{ kWh}$
$26.4\text{kWh} \times \text{RM}0.218/\text{kWh} = \text{RM } 5.80$	Cost	$60\text{kWh} \times \text{RM}0.218/\text{kWh} = \text{RM } 17.40$
$26.4\text{ kWh} \times 0.34\text{ total kg CO}_2\text{e per kWh} = 8.976\text{ total kg CO}_2\text{e}$	Carbon footprint	$60\text{kWh} \times 0.34\text{ total kg CO}_2\text{e per kWh} = 27.200\text{ total kg CO}_2\text{e}$

Conclusions

In conclusion, based on the optimum moisture point of the soil, the new mixing ratio was determined by increasing the water content from 10 to 15 in terms of ratio. The optimum performance of the mix ratio of laterite soil, sodium silicate solution, sodium hydroxide solution, and water for each type of brick sample was 100: 9: 5: 15. Furthermore, in terms of compressive strength and water absorption characteristics, both types of brick samples from each ratio can be applied as load-bearing class 1, internal wall brick in Malaysia Standard, all types of brick except engineering, facing and damp-proof course brick in British Standard, third-grade brick in Singapore Standard, non-weathering building brick in American Standard, and all in Australia Standard. Additionally, according to the Malaysian Standard, LAT 2 and LAT 3-based bricks at a ratio of 1.5 of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ can also be used as load-bearing brick class 2. In this research, strong long-chain silicate oligomers were increased as the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio was increased, which can enhance the strength and durability of the brick. Besides, the high compactness of a well-graded structure contributes to the high performance of geopolymer brick with less porosity. Last but not least, non-fired brick is an environmentally friendly material that can be used in green buildings because the brick manufacturing process effectively reduces the power consumption, electric cost, and carbon footprint of power generation.

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